

An *RXTE* Archival Search for Coherent X-ray Pulsations in LMXB 4U 1820–30

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Abstract. As part of a large-scale search for coherent pulsations from LMXBs in the *RXTE* archive, we have completed a detailed series of searches for coherent pulsations of 4U 1820–30 — an ultracompact LMXB with a binary period of 11.4 minutes located in the globular cluster NGC 6624. The small binary period leads to a very high acceleration, so we used phase modulation searches as well as acceleration searches to give significant sensitivity to millisecond pulsations. We searched a total of 34 archival *RXTE* observations, 32 of which had an on-source integration time longer than 10 ks, and some of which were made consecutively which allowed us to combine them. While we found no pulsations, we have been able to place the first stringent (95% confidence) pulsed fraction limits of $\lesssim 0.8\%$ for all realistic spin frequencies (i.e. $\lesssim 1$ kHz) and likely companion masses ($0.02 M_{\odot} \leq M_c \leq 0.3 M_{\odot}$). By contrast all five LMXBs known to emit coherent pulsations have intrinsic pulsed fractions in the range 3% to 7% when pulsations are observed.

INTRODUCTION

One of the great scientific expectations when the Rossi X-ray Timing Explorer (*RXTE*) was launched in 1995 was the discovery of coherent pulsations from low-mass X-ray binaries (LMXBs). At present, only five accreting millisecond pulsars are known. All five are faint transient sources where the pulsations at the spin period of the pulsar were discovered during an outburst (see the contributions of D. Chakrabarty and C. Markwardt to the proceedings of this conference).

There are many things that we can learn from searching for more examples of direct pulsations from LMXBs. For example, coherent pulsations give the precise rotation rate of the neutron star and test the connection between recycled MSPs and LMXBs. They help constrain the models of kHz QPOs and burst oscillations. Timing of the coherent pulses would also allow measurements of the accretion torques, the orbital parameters, and the companion masses. In addition, along with X-ray and optical spectra, pulse timing can give information about the compactness and the equation of state of the neutron star. Finally, setting stringent upper limits to coherent pulsations in several sources in a variety of spectral states will impose constraints on the possible mechanism for suppressing coherent pulsations in these sources. For all these reasons, we have started a large-scale search for coherent pulsations from LMXBs.

CHARACTERISTICS OF 4U 1820–30

The source 4U 1820–30 is an atoll LMXB in globular cluster NGC 6624. It has an orbital binary period of 685 s (11.4 min) [1], the shortest known binary orbital period in an LMXB. 4U 1820–30 undergoes a regular ~ 176 day accretion cycle [2] switching between high and low luminosity states. In the low state, regular Type I bursts are seen ± 23 days around the minimum luminosity [3]. In the low state, 4U 1820–30 has also shown an extremely energetic superburst, likely due to deep ignition of a carbon layer [4]. Several low frequency QPOs [5] as well as two peaks of kHz QPOs [6] have been observed from this source. Faint UV and optical counterparts of 4U 1820–30 have also been observed [7, 8]. If the secondary star in the system is a white dwarf, its mass is estimated to be 0.058 to 0.078 M_{\odot} [9]. If the secondary is a main sequence star, the upper limit on its mass is 0.3 M_{\odot} [10].

Of all known LMXBs, we searched 4U 1820–30 first because a lot of high time resolution long data sets of this source are available in the archives, because the presence of kHz QPOs in this source may indicate favorable conditions for detecting pulsations, and because of its small orbital period: the phase modulation search technique that we are using is most sensitive (and provides the biggest increase in sensitivity over previous methods) when the observations are longer than two complete binary orbits [11].

THE *RXTE* OBSERVATIONS

We searched 34 archival *RXTE* observations collected between 1996 and 2002. The observations were available in event modes, and had a time resolution of $125 \mu\text{s}$ or better. 32 of the observations had a total time on source bigger than 10 ks. The longest of these was 25 ks long with a total time on source of 16 ks. Some of the observations were segments of longer observations which allowed us to concatenate them and analyse them together. The longest of the concatenated observations was 77.5 ks long with a total time on source of 46.5 ks.

THE DATA ANALYSIS

Each observation was downloaded, filtered, barycentered, and then split into four energy bands: Soft (2-5 keV), Medium (5-10 keV), Hard (10-20 keV), and Wide (2-20 keV), in order to attempt to maximize the signal-to-noise ratio of the unknown pulsations. This processing used custom Python scripts that call the standard FTOOLS. The processed events were then binned into high time resolution (either 0.122 ms or 0.244 ms) time series. Fast Fourier Transforms of the four time series were then computed. Acceleration searches of FFTs of various durations were performed. ‘Phase-Modulation’ searches were conducted on each of the full duration FFTs. Finally, candidates above our threshold were examined using brute-force folding techniques to determine if they were true pulsations.

THE SEARCH TECHNIQUES

After we prepared and binned the data sets, we searched them for pulsations in the Fourier domain using two types of searches which we summarize below.

Acceleration Searches

This is the method traditionally used to compensate for the effects of orbital motion [12, 13, 14, 15, 16]: A time series is stretched or compressed appropriately to account for a trial constant frequency derivative (i.e. constant acceleration), Fourier transformed, and then searched for pulsations. We used a Fourier-domain variant of this technique [17]. Unfortunately acceleration searches can detect only the strongest pulsations from systems like 4U 1820–30 where the orbital period is short. So while we did not expect acceleration searches to find pulsations, we still used them because they are in-

cluded in the standard search pipeline that we are going to use to search the other sources.

Phase Modulation Searches

In order to analyze longer observations we used a new ‘phase-modulation’ or ‘sideband’ search technique [11]. This technique relies on the fact that if the observation time is longer than the orbital period, the orbit phase-modulates the pulsar’s spin frequency: phase modulation results in a family of evenly spaced sidebands in the frequency domain, around the intrinsic pulsar signal. The constant spacing between the sidebands is related to the binary orbital period.

A phase modulation search is conducted by taking short FFTs of the power spectrum of a full observation. The short FFTs cover overlapping portions of various lengths (to account for the unknown semi-major axis of the LMXB) over all the Fourier frequency range of the original power spectrum (to account for the unknown pulsation period). They are then searched for peaks indicating regularly spaced sideband (to detect the orbital period of the LMXB). A detection provides initial estimates of the pulsar period, the orbital period, and the projected radius of the orbit, which are refined by generating a series of complex-valued template responses to correlate with the original Fourier amplitudes (i.e. matched filtering in the Fourier domain) [11].

RESULTS AND UPPER LIMITS

Our searches did not detect pulsations.

To set an upper limit on the pulsed fraction of detectable pulsations from 4U 1820–30 we used the following procedure: we ran our searches on several data sets containing simulated pulsations of various pulsed fractions for a range of companion masses (see Figure 1) and for several spin frequencies. For the purpose of the simulations, we assumed an orbital period of 685 seconds, the typical length of a long *RXTE* observation (20.5 ks), an inclination angle of 60 degrees, and a circular orbit. Of the searches that we ran, phase modulation searches run on the full duration data sets were the most sensitive. Figure 1 shows the results of the simulations for this type of search run on data sets containing fake 3 ms pulsations. Every point in the figure corresponds to 100 searched data sets. The shading of every point corresponds to a sigma detection level. The line of $\sigma = 5$ indicates the value of our upper limit on the pulsed fraction for a signal period of 3 ms. This value varied between 0.55% and 1.0% (background subtracted) over the range of companion masses that we used. The value de-

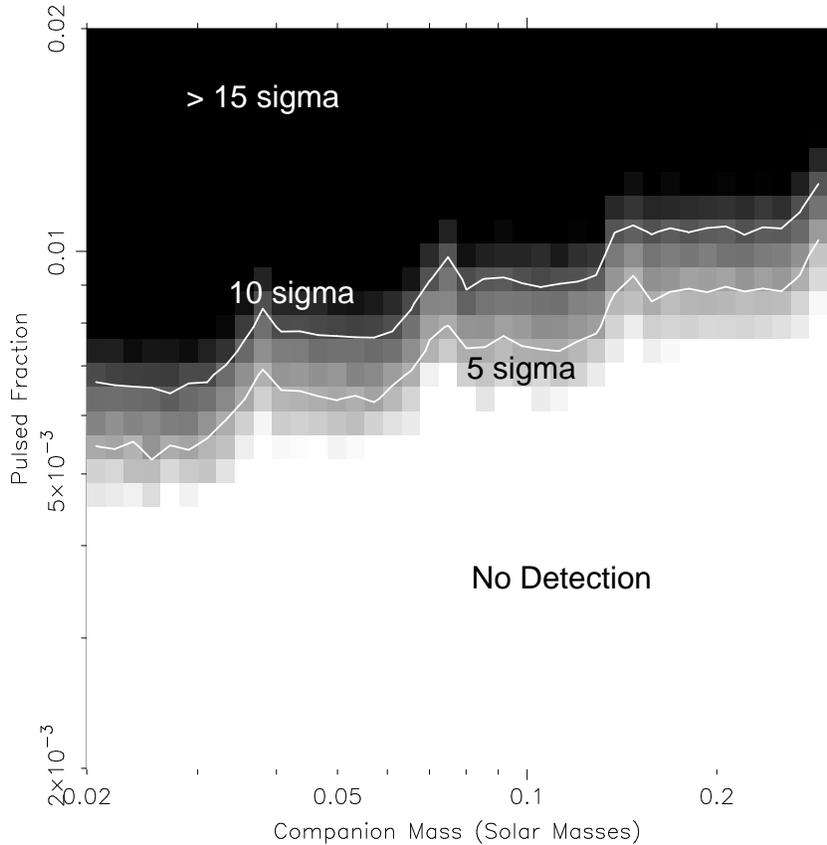


FIGURE 1. Monte-Carlo derived sensitivity calculations for the pulsation searches of archival RXTE observations of 4U 1820–30. The plotted sensitivities are 95% confidence limits using phase modulation search technique for a typical RXTE observation assuming a pulsar spin period of 3ms. We would easily have detected any coherent pulsations with a pulsed fraction $> 0.8\%$ for all realistic companion masses and spin periods.

creased slightly when the period of the signal was larger by a few milliseconds. This means that if there were a 3 ms coherent pulsation coming from 4U 1820–30 with a pulsed fraction equal or higher than the upper limit stated above, our searches would have easily (with a 95% confidence) detected it.

Our upper limit on the pulsed fraction of possible signals from 4U 1820–30 was about 0.8% (background subtracted) for spin periods under 10 ms. The pulsed fractions of the signals detected from the 5 LMXBs with known signal period ranged between 3% and 7%, for signal frequencies between 2 ms and 6 ms [18, 19, 20, 21]. This means that our searches would have detected the pulsations from 4U 1820–30 if they were as strong as the pulsations detected from the other 5 sources and in the same period range.

POTENTIAL REASONS FOR THE LACK OF OBSERVED PULSATIONS

Several theories exist to explain why pulsations with a higher pulsed fraction than our upper limit are not seen. To begin with, an unfavorable rotational geometry, an unfavorable viewing geometry, or both can make pulsations undetectable. The pulsed fraction may be reduced due to scattering in the surrounding medium [22]. Gravitational lens effects on the emission from the hot polar caps can also greatly reduce the pulsed fraction [23, 24]. Finally, screening of the stellar magnetic field by the accreting matter can lead to a less preferential heating of the surface (i.e. no polar caps) and therefore to the absence of observable pulsations [25].

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